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Production of the neutron-rich nuclides ^{20}C and ^{27}F by fragmentation of 213 MeV/nucleon ^{48}Ca

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Production cross sections of neutron-rich projectile fragments have been measured for the reaction 213 MeV/nucleon $^{48}Ca+Be$. The neutron-rich nuclides ^{20}C and ^{27}F have been observed for the first time. A method to strengthen our evidence for the possible particle stability of ^{21}C, ^{23}N, and ^{25}O is presented.

[RADIOACTIVITY First observation of ^{20}C and ^{27}F produced in fragmentation of 213 MeV/nucleon ^{48}Ca.]

Of the more than 7000 nuclides predicted to be particle stable, only about one-fourth have ever been observed. The actual limits of particle stability, the so-called neutron and proton driplines, are known only up to beryllium for neutron-rich nuclides and up to sodium for proton-rich nuclides. A more complete knowledge of the location of the driplines would have widespread implications for both nuclear physics and nuclear astrophysics.

Among the methods used to predict the masses of nuclei far from the valley of stability are the droplet model,[1-3] the shell model,[4,5] self-consistent calculations based on the energy density concept,[6] and the Garvey-Kelson mass relations.[7-10] These models contain parameters chosen to fit known masses of nuclei near the valley of stability. Predictions of the limits of particle stability of nuclides require considerable extrapolations from the fitted data and therefore provide a good test of the global validity of these models. Techniques to produce extremely neutron-rich nuclides include proton-induced fragmentation of heavy nuclei,[11] deep inelastic heavy-ion reactions,[12] and fragmentation of relativistic heavy ions.[13,14]

In this paper we report results of a search for new neutron-rich nuclides produced by fragmenting 213 MeV/nucleon ^{48}Ca nuclei. These results include the discovery of the particle stability of ^{20}C and ^{27}F, confirmation of a previous report of the particle stability of ^{22}N and ^{26}F,[14] and evidence for the possible particle stability of ^{21}C, ^{23}N, and ^{25}O.

The process of relativistic heavy-ion projectile fragmentation has been studied extensively.[15,16] Projectile fragments viewed in the projectile frame have Gaussian transverse and longitudinal momentum distributions,[15] with momentum widths $\sigma_{p_{\parallel}} \simeq \sigma_{p_{\perp}} \approx 200$ MeV/c. In the laboratory frame the fragments are "focused" within $\sim 1°$ of the beam direction and have a momentum per nucleon within a few percent of that of the beam. By passing this beam of fragments through a spectrometer, neutron-rich nuclei are cleanly separated from stability-line isotopes which are $\sim 10^6$ times more abundant.

The experimental techniques used in this experiment are described in detail in Ref. 17. The zero-degree magnetic spectrometer at the Lawrence Berkeley Laboratory Bevalac was used to focus neutron-rich projectile fragments on a stack of Lexan plastic track detectors[18] thick enough to stop fragments with $Z > 5$. Later the detectors were chemically etched and the sizes and positions of the etch pits at the ends of range of the fragments that stopped in the stack were measured with a microscope. The range of each fragment, its deflection in the spectrometer, and its charge at the end of its range were determined from the etch pit measurements. The charge resolution was $\sigma_Z \approx 0.2$, as demonstrated by the charge spectrum in Fig. 1. Absolute charge assignments were based on calibrations of the plastic detectors with low-energy ^{12}C and ^{16}O ions. The absolute charge assignments were cross checked by calculating the average energy per nucleon of the observed fragments. An error in charge assignment of one charge unit would result in an average fragment

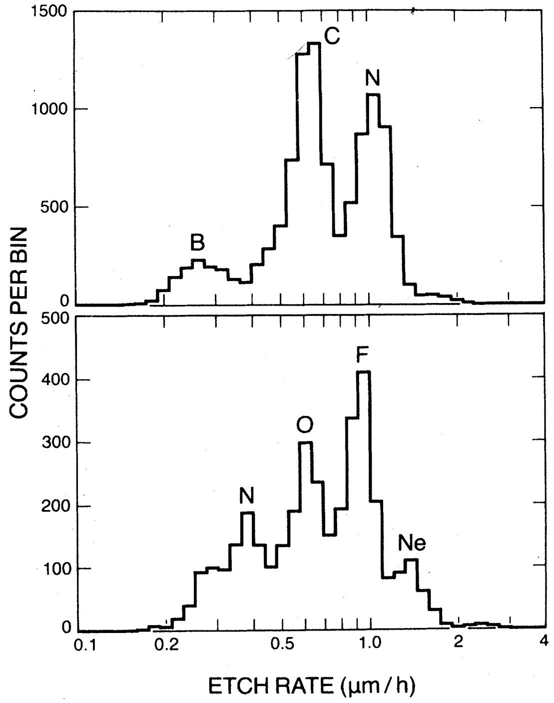

FIG. 1. Charge histograms of elements observed in this experiment. The sensitivity of the plastic detectors was increased by exposure to ultraviolet light. The sensitivity of the detectors used to obtain the top histogram is ~ 3 times higher than the sensitivity of the detectors used to obtain the bottom histogram.

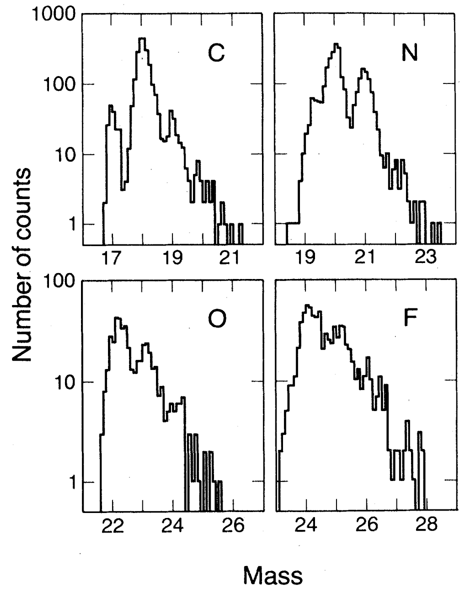

FIG. 2. Mass histograms of neutron-rich isotopes of C, N, O, and F observed in this experiment. The peak heights do not directly reflect the relative abundances of the isotopes.

energy differing from its predicted value by about 7%. The average fragment energy agreed with the predicted value to within less than 1%. The energy of the beam was determined by measuring its range (to $\pm 1\%$) in a stack of plastic detectors. In addition, the deflection of the beam was measured (to $\pm 0.3\%$) by measuring the position of the beam in the plastic detector stack. This measurement provided an absolute calibration of the spectrometer itself. The rigidities of the fragments were found by comparing their deflections to that of the beam. The charge, range, and rigidity measurements allowed the mass of each particle to be calculated. The absolute mass scale was determined to $\lesssim 0.2$ u by the range and deflection measurements of the beam. The beam intensity of ^{48}Ca ions, $\sim 10^7$ ions/sec, was monitored with a scintillator telescope that counted fragments from the target. The monitor was calibrated at intensities low enough to count. The target was 0.89 g/cm^2 beryllium.

Figure 2 shows data accumulated over a 40 h run, for carbon, nitrogen, oxygen, and fluorine nuclei. The mass resolution ranges from $\sigma_m \simeq 0.23$ for carbon to $\sigma_m \simeq 0.33$ for fluorine. The ratios of peak heights do not directly reflect the relative yields of isotopes.

There is clear evidence for the first observation of ^{20}C (~ 40 counts) and ^{27}F (~ 20 counts). We also confirm the particle stability of ^{22}N and ^{26}F, which were recently reported.[14] In addition, at ^{21}C, ^{23}N, and ^{25}O there are bumps consisting of about five counts clearly outside the Gaussian envelopes of the adjacent lighter isotopes. Although the number of counts is too small to establish convincingly their existence, it should be possible with small improvements in sensitivity to obtain definitive evidence.

To determine fragmentation cross sections we calculated the transmission through the spectrometer assuming that the fragment momentum distributions viewed in the projectile frame were Gaussian with σ given by

$$\sigma = 94[M_f(M_p - M_f)/(M_p - 1)]^{1/2}\ \text{MeV}/c, \tag{1}$$

where M_f and M_p are the fragment and projectile masses in u. This equation was shown[16] to fit the measured momentum widths for the reaction 213

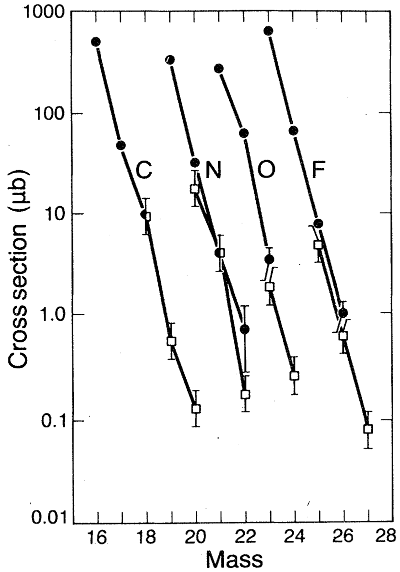

FIG. 3. Measured cross sections for production of neutron-rich isotopes in the 213 MeV/nucleon ^{48}Ca+Be reaction. Solid circles are results of Ref. 14; open squares are present.

MeV/nucleon ^{40}Ar+C→ projectile fragments. Figure 3 compares our calculated fragmentation cross sections with those of Westfall *et al.*[14] for exactly the same reaction, 213 MeV/nucleon ^{48}Ca+Be. The absolute normalization of our results is somewhat uncertain but is in reasonable agreement with the work of Westfall *et al.* Because our Lexan detector stack was much larger than the detector telescope used by Westfall *et al.*, we were able to survey a wider rigidity interval and detect nuclides more neutron-rich and with lower production cross sections despite the fact that our total fluence of ^{48}Ca ions was smaller than theirs.

Table I gives the mass excess calculated by several methods for nuclides in the vicinity of the neutron dripline for C, N, O, and F. Single and double asterisks signify nuclides calculated to be unstable against single and double neutron emission, respectively. Although the nuclides ^{20}C and ^{27}F that we have detected are calculated to be particle stable by each of the models, it is interesting to note that ^{21}C and ^{25}O, for whose existence we have some evidence, are calculated to be unstable against neutron emission by some of the models and particle stable by others. ^{24}N and ^{28}F are also predicted by several models to be particle unstable.

Judging from the trends in Fig. 3, an experiment capable of discriminating among these models will require about 50 times the present sensitivity, using the 213 MeV/nucleon ^{48}Ca+Be reaction. One possible way of achieving this is to use considerably thicker targets. Figure 4 shows the expected

TABLE I. Mass excesses for some neutron-rich nuclides (in MeV). Single and double asterisks signify nuclides calculated to be unstable against single and double neutron emission, respectively.

	Particle stable?	Calculated mass excess Ref. 2	Ref. 4	Ref. 6	Ref. 8	Ref. 9
^{19}C	yes[a]	33.38*		30.0	33.57*	33.55
^{20}C	yes[b]	37.33		33.9	36.95	37.17
^{21}C	yes?[b]	47.34*		41.1	45.22*	46.01*
^{22}C		53.51**		47.4	50.63	51.72
^{22}N	yes[c]	33.08*			30.72	31.54
^{23}N	yes[b]	38.06		31.7	36.13	37.27
^{24}N		47.76*			45.08*	46.04*
^{25}N		53.87		49.4*	52.81**	53.17
^{25}O	yes?[b]	29.64*	28.99	24.7*	28.18*	28.91*
^{26}O		34.75	33.66	31.6	34.13	33.97
^{26}F	yes[c]	19.15	16.95		18.60	18.84
^{27}F	yes[b]	23.15	20.91	21.2	23.70	23.06
^{28}F		31.54*	28.71		32.58*	31.06

[a]Reference 19.
[b]This work.
[c]Reference 14.

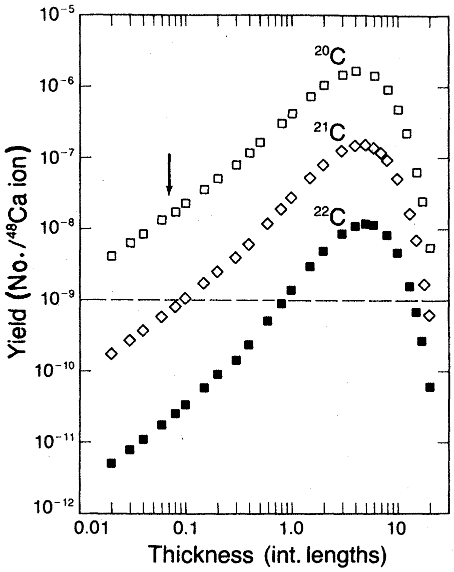

FIG. 4. Calculated yield of neutron-rich carbon ions per ^{48}Ca ion as a function of target thickness. The calculation assumes a Gaussian mass yield fitted to measured cross sections. The arrow indicates the target thickness for this experiment and that of Ref. 14. The dashed line corresponds to a yield of 10 events with present beam intensities and a detector with collecting power comparable to ours.

yield of carbon isotopes as a function of target thickness, calculated on the assumption that the partial cross section for isotopes of a given element has a Gaussian dependence on fragment mass about a most probable mass, with a mass width taken to be a constant $\sigma_A = 1.5$ u. This prescription, together with appropriate normalization factors and a geometrical total cross section, gives reasonable agreement with the production cross sections of neutron-rich nuclei found by Westfall *et al.*[14] and in our Fig. 3.

The arrow in Fig. 4 indicates the target thickness for our experiment and that of Westfall *et al.* The dashed horizontal line assumes present beam intensities and only ten events. The predicted yield increases somewhat faster than linearly with target thickness because of multiple interactions in the target. One can see that, with current Bevalac beam intensities, experiments with very thick (~ 1 interaction length) targets may well have the sensitivity to test the limits of particle stability. Improvements in the Bevalac will soon provide higher beam intensities and ions up to Pb or U. Thus, fragmentation of relativistic heavy ions promises to be a powerful tool in the study of nuclei far from stability.

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